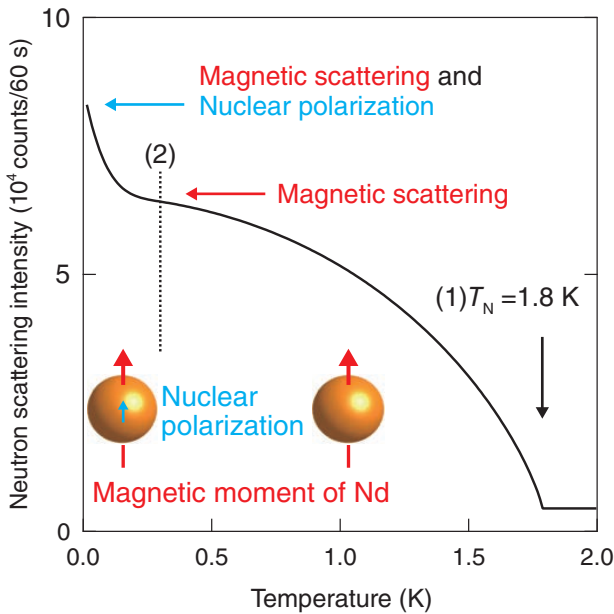


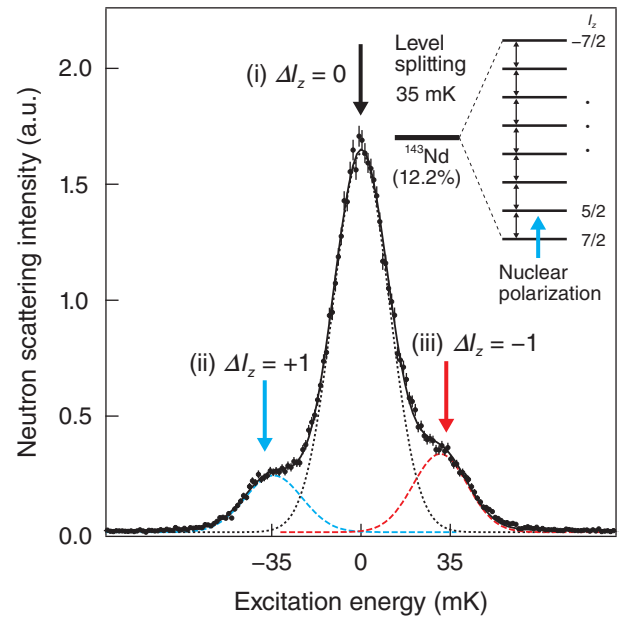
## 5-4 Neutron Scattering Measurements for Magnetic Moment in Comparison with Nuclear Spin Polarization — A New Technique Useful in Study on Magnetism and Material —



**Fig.1 Temperature dependence of neutron scattering intensity**  
We focus on the magnetic element with nuclear spin polarization. The magnetic moment can be estimated by comparing the magnetic scattering (horizontal red arrow) with the increase in intensity due to the nuclear spin polarization (horizontal blue arrow).

Magnetic moments, which are important for magnets, motors, storage devices, etc., differ in magnitude even with the same magnetic element, depending on the electronic structures of magnetic materials; hence, these moments should be measured. Neutron magnetic scattering is a powerful tool for this purpose. However, a high-quality single crystal is necessary to obtain a large data set of hundreds of diffraction intensities that are corrected appropriately. We obtained the magnetic structure and the moment magnitude after a complete structural analysis of such data. Each scattering intensity contains contributions from all atoms in a unit cell. We developed a method to measure the magnetic moment by comparing the magnetic scattering intensity with the scattering of the on-site nuclear spin polarization. We focused on a magnetic element by the on-site interference of neutron scattering from the magnetic moment and the induced nuclear spin polarization. The moment can be determined conveniently and precisely only from a single reflection; thus, no structural information is necessary in many cases. Magnetic elements can also be distinguished from the nuclear spin polarization.

The magnetic scattering intensity of Nd moment (thick red arrow) in  $\text{Nd}_3\text{Pd}_{20}\text{Ge}_6$  (neodymium–palladium–germanium) increases in the magnetically ordered phase (1) below the Néel temperature  $T_N = 1.8$  K and exhibits (2) a clear up-turn, which is the contribution from  $^{143}\text{Nd}$  nuclear spin polarization (blue



**Fig.2 Hyperfine spectrum of  $^{143}\text{Nd}$  nuclear spin states**

$^{143}\text{Nd}$  nuclear is spin polarized below the temperature corresponding to the level splitting of the  $^{143}\text{Nd}$  nuclear spin states about 35 mK. Thus, the increase in the neutron scattering intensity shown in Fig.1(2) originates from the contribution of this nuclear spin polarization.

arrow) at very low temperatures (Fig.1). The Nd moment was estimated by comparing the magnetic scattering with the nuclear spin contribution, which is known with great accuracy.

The existence of the nuclear spin polarization was confirmed by measuring the hyperfine spectra of  $^{143}\text{Nd}$  nuclei (natural abundance 12.2%) with a nuclear spin  $I = 7/2$  in the magnetically ordered phase as shown in the inset of Fig.2. The three peaks in Fig.2 correspond to transitions with (i)  $\Delta I_z = 0$  (black arrow) at  $\Delta E = 0$ , (ii)  $\Delta I_z = +1$  (blue arrow) at  $\Delta E = -35$  mK, and (iii)  $\Delta I_z = -1$  (red arrow) at  $\Delta E = +35$  mK. Here,  $\Delta I_z$  is the change of  $I_z$  after the excitation, and  $\Delta E$  is the excitation energy expressed in temperature units. The observed excitation energies of  $\Delta E = \mp 35$  mK for  $\Delta I_z = \pm 1$  give the level splitting. Thus, the increase in the neutron scattering intensity as shown in Fig.1(2) at very low temperatures originates from this nuclear spin polarization.

This method can be applied for the magnetic elements with appropriate nuclear spins. It will be very interesting to expand its applications to clarify complex crystal and magnetic structures, which cannot be easily resolved by the conventional structural analysis of diffraction data. Furthermore, this method can be applied to develop magnetic materials for strong magnets and to clarify their mechanisms.

(Naoto Metoki)

### Reference

Metoki, N. et al., Hyperfine Splitting and Nuclear Spin Polarization in  $\text{NdPd}_5\text{Al}_2$  and  $\text{Nd}_3\text{Pd}_{20}\text{Ge}_6$ , Journal of the Physical Society of Japan, vol.91, no.5, 2022, 054710, 6p.